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Environmental decision-support systems for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants

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Abstract

Today's environmental policies are largely devoted to fostering the development and implementation in Europe of renewable energy technologies, such as grid-connected photovoltaic solar energy, which are being actively promoted by European Union countries. This article describes an environmental decision-support system (EDSS) for selecting optimal sites for grid-connected photovoltaic power plants. This system combines multicriteria analysis and the analytic hierarchy process with geographical information systems (GIS) technology and at the same time takes into account environment, orography, location, and climate factors.

Keywords: Environmental decision-support systems; Renewable energy; Photovoltaic systems

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Contents

1. Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change, which was adopted in December 1997, marks a crucial turning point in the effort to promote the use of renewable energy [1]. In the same line, the European Union also adopted the Green Paper, which opened the debate on renewable sources of energy, more specifically, measures to be taken, objectives to achieve, obstacles to overcome and the means that should be deployed to do this [2].

Renewable energy technologies are popular because useful power output can be obtained with little or no energy input and, subsequently, environmental loads are very low [3]. In this sense, Spain has taken an important step forward in fomenting grid-connected photovoltaic solar energy with its Royal Decree 436/2004 [4], a national law that regulates the premiums to be paid for the sale of electrical energy produced by renewable energy systems. This law may provide additional stimulus for solar photovoltaics because it increases the incentive to 41 €cents/kWh for power plants smaller than 100 kW, and 21 €cents/kWh for larger plants. The feed-in tariff also introduces a guarantee of 25 years from the date of commissioning. This stability follows the highly successful German model. Between 2001 and 2004 installations of photovoltaic systems in the European Union more than tripled, and reached a cumulative 1 GW of installed power capacity at the end of 2004. Almost 80% of the total number of photovoltaic plants in the European Union was installed in Germany [5]. Considering actual market prices, and depending on installation costs and electricity production capacity, the recovery of an investment in a grid-connected photovoltaic power plant (GGGP) of 100 kWp takes approximately 10 years [6].

Currently, there is active support for such measures in Spain since the solar photovoltaic cell and solar photovoltaic installation industry in this country is a highly competitive sector and well known for its high quality, flexibility, innovation, and commercial

dynamism. In fact, Spain is the leading European manufacturer of solar power, exporting 85% of its production. This amounts to 40% of the photovoltaic (PV) production in Europe, and 7% of the PV production worldwide [7].

In terms of solar energy output and performance, southern Spain, in particular the region of Andalusia, is regarded as one of the most optimal sites in the world for the installation of photovoltaic solar energy systems. Its climate has a high number of sun hours per year and excellent levels of solar irradiance [8,9]. Moreover, much of its surface area is orographically suitable for this type of installation. The land is either flat or has very mild slopes. It also has a low agricultural value as well as an extensive power transmission grid to absorb the electricity generated.

Such favorable climate conditions and legal measures, as well the greater availability of photovoltaic energy for purchase, produced an increase of 10–26 MWp from 2004 to 2006. The objective is to reach 400 MWp in 2010 [10].

For all of these reasons, in the near future it is very likely that a growing number of grid-connected photovoltaic power plants will be built in Spain, mostly in Andalusia. However, it is imperative that project designers have access to local information on climate and soil characteristics. Without such data, optimal site selection for solar power installations cannot be guaranteed. Basing site selection on a wide range of information offers the following advantages:

(1) enhanced performance of the installation, if the site has suitable climate conditions; in other words, high levels of solar irradiance, moderate temperatures, high number of sun hours per year, etc.;
(2) optimization of the installations when they are built on flat ground, oriented towards the south, and without shadow-producing obstacles;
(3) lower transport losses if a distributed generation system is used, and electrical production plants near urban areas, which are the main consumption points;
(4) lower maintenance costs throughout the installation's useful life if the site is well-connected to nearby urban areas;
(5) minimal impact on the environment, society, and infrastructures.

Site selection for grid-connected photovoltaic power plants (GPPPs) can be regulated by means of a carrying capacity model, which combines multicriteria analysis as well as the analytic hierarchy process (AHP) with geographical information systems (GIS) technology. This article defines the structure and the principal phases of an environmental decision-support system geared to facilitate site selection for GPPPs.

2. Environmental decision-support systems

When there is a problem in any context, an effort must be made to solve it, and this involves making decisions. However, in the context of decision- making in territorial management, any decision generally entails a specific distribution of resources [11]. Decision-support systems (DSS) are a new generation of information systems, whose objective is to discover what would happen if a series of decisions are taken. Such systems can even automatically provide decisions and suggestions that can help and guide the task manager [12].The generic nature of DSS has led to the creation of systems that focus on specific types of problems. When such systems are applied to environmental problems, they

are generally known as environmental decision-support systems (EDSS) [13]. Many EDSS applications require a great quantity of spatial information in order to visualize the results as well as to facilitate the decision-making process. GIS are essential for such a task, and can be used as a flexible type of EDSS.

GIS [14] can be defined as an integrated collection of computer software used to analyze, create, acquire, store, edit, transform, view, and distribute geographic data. Still another definition underlines its wide range of capacities, defining a GIS as a system of hardware, software, and procedures to facilitate the acquisition, management, manipulation, analysis, modeling, representation, and output of spatially referenced data to solve complex planning and management problems [15].

In recent years GIS have become increasingly popular as a tool for territorial planning [16], and for the selection of optimal sites for different types of activities and installations [17]. In the services sector [18,19] GIS have been used as a geomarketing tool.

Despite the fact that GIS software applications all resemble each other to a certain degree, some applications are more suitable than others for specific tasks. For example, GIS such as ArcGIS, handle data in the form of vectors (points and lines), whereas other GIS applications, such as IDRISI or ArcView, are raster systems that use cells or pixels.

Since the management of complex GIS databases necessarily entails the need to organize and process large quantities of information, this means that techniques such as multicriteria evaluation (MCE) should be used in combination with GIS. MCE techniques are valuable procedures for carrying out territorial planning tasks. Their benefits have been demonstrated in a great variety of studies [20,21].

The abundance of research in this area is indicative of the tendency to use MCE techniques to mitigate the analytical deficiencies characteristic of GIS [14]. This integration has made possible what is known as "participative decision-making" in which the public can directly access information, for example, regarding community planning processes, and give their opinions [22].

Furthermore, MCE methods are frequently integrated in GIS, when it is necessary to select the best site for a certain activity. It is thus possible to obtain continuous suitability maps, and to thus provide an optimal framework for the integration of the environmental, economic, and social factors that affect land suitability for a certain use.

Among the various MCE techniques that can be applied to the evaluation of land suitability, the weighted linear sum is the simplest and, hence, is most frequently used [23,24].

Given the fact that there are multiple variables that affect the selection of optimal sites, we decided to use the AHP [23,24]. This method represents a specific problem by means of the hierarchical organization of criteria, and afterwards uses comparisons to establish weights for criteria and preference scores for classes of different criteria, based on user judgment. To validate this model, in the following sections we present a case study of the northeast sector of the province of Granada (Andalusia, Spain).

3. Defining the decision-making model

There are various MCE methods, each of which differs in its respective characteristics, evaluation, data type, and objectives [14]. For example, depending on the number of

objectives and criteria considered, the following combinations are possible [25]: (i) one objective and one criterion, (ii) one objective and several criteria and (iii) several objectives and several criteria.

In the end it is the decision-maker who, depending on the problem to be resolved, must choose the most suitable method. On the basis of all of these variables, MCE methods can be classified into three general groups [25]:

- *Compensatory techniques*: These techniques require a greater cognitive weight since the decision-making center must assign weights to the criteria in the form of a decision-making rule. They are based on the premise that a high value for one alternative can be compensated by a low value for the same alternative with regard to other criteria. For example, land with excellent climate characteristics can have a lower value if the factor land use is taken into account. Within this group of techniques the most important methods are the weighted linear sum, AHP, concordance analysis, and ideal point analysis. The weighted linear sum is one of the most frequently used methods because of its simplicity. Precisely for this reason, it is included in 36 of the 41 discrete MCE programs described in Barba-Romero and Pomerol [26]. However, the analytic hierarchy process has the following advantages:
    - it allows qualitative evaluations [27];
    - elements are assigned weights, which are used as decision-making criteria [27];
    - a sensitivity analysis of the results can be carried out [27];
    - a consensus can be obtained among decision makers and stakeholders, since this technique facilitates communication between different groups of people [28];
    - it identifies and accounts for inconsistencies of decision-makers since their judgments are rarely totally in consonance with qualitative factors [29];
    - it can deal with complex real-world problems. After comparing this technique with five other models to determine weights and priorities, the results of the AHP were found to be more reliable than the results of other models [30].
- *Non-compensatory techniques*: These techniques require a smaller cognitive weight since they only assign an ordinal value to the criteria [31].
- *Fuzzy techniques*: These techniques deal with problems whose boundaries are not clearly defined. Fuzzy logic arose as an alternative to binary logic (1/0, true/false, etc.), and is now used in a wide range of fields and disciplines. In geography there are many examples of such representations [14,17]. Fuzzy techniques include the fuzzy weighted sum and ordered weighted averaging (OWA).

The model described in this article is a system based on MCE with one objective and several criteria. It uses Saaty's AHP because in our opinion, AHP can handle decision-making problems which require a high degree of flexibility and reliability. This is one of the reasons why this method is currently used for fuzzy decision-making [32] and mathematical programming.

The phases of the elaboration of the decision-making model are shown in Fig. 1 [16]: (i) definition of objectives, (ii) specification of criteria, (iii) establishment of the decision rule, (iv) calculation of inconsistency, (v) determination of the suitability of the land area for grid-connected photovoltaic power plants.

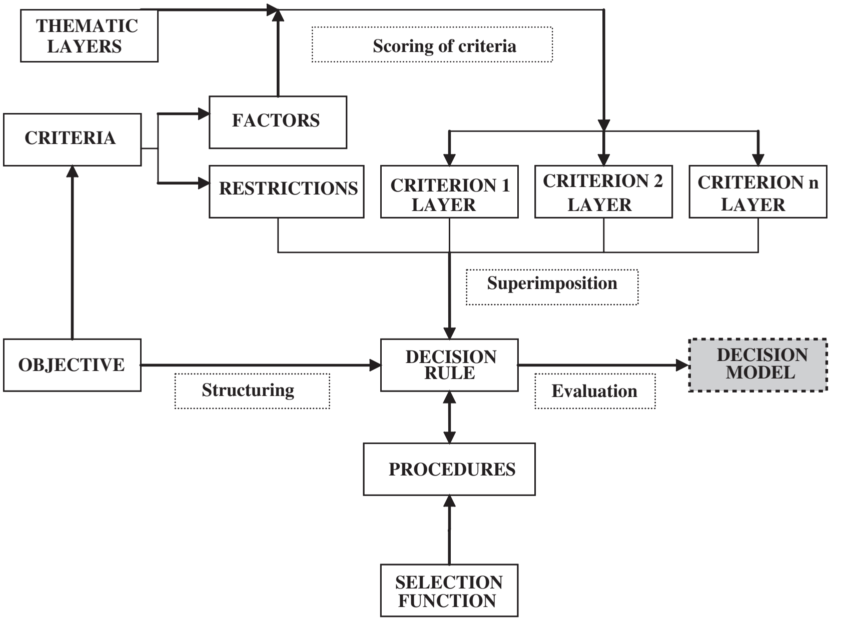

Fig. 1. Flow chart of the elaboration of the decision model.

3.1. *Objective of the method*

The MCE defines an objective as a function to be developed, and governs the structuring of the decision rule [33] or indicates the type of decision rule to use. The objective of this research is the designation of optimal sites for grid-connected photovoltaic power plants, which fulfill the requirements established by the decision rule.

3.2. *Definition of criteria*

A criterion is a measurable aspect of a judgment, which makes it possible to characterize and quantify alternatives in a decision-making process [33,34]. The criteria chosen for this study can be classified in four groups: environment, orography, location, and climate. These criteria can be subdivided into factors, which are those attributes of the land area that best characterize the suitability of an alternative in reference to the activity, and which should be selected for their measurement on a continuous scale [33].

Each of these factors is determined by indicators, defined as magnitudes that measure or rate a factor. Indicators can be classified in two groups: (i) positive indicators, (ii) negative indicators or restrictions. Positive indicators are those that enhance the suitability of an alternative. Examples of such indicators are areas with no vegetation, with a southwards orientation, etc. (see Table 1). In contrast, negative indicators restrict alternatives, depending on the activity evaluated [16]. Examples of such restrictions are legal requirements and environmental protection laws such as the right to highway, river, and

Table 1
Positive and negative indicators

Criteria	Factors	Indicators
Environment	Land use	Area without vegetation
		Dryland herbaceous crops
		Irrigated herbaceous crops
		Herbaceous and woody crops
		Woody crops
		Other uses
	Visual impact	Areas with minimum-value scenery
		Areas with value-2 scenery
		Areas with value-3 scenery
		Areas with value-4 scenery
		Areas with value-5 scenery
		Areas with value-6 scenery
		Areas with value-7 scenery
		Areas with value-8 scenery
		Areas with value-9 scenery
		Areas with maximum-value scenery
Orography	Slopes	$<3\%$
		4%–6%
		7%–9%
		10%–12%
		13%–15%
		16%–18%
		19%–21%
		22%–24%
		25%–27%
		28%–30%
		$>30\%$
	Orientation	South
		Southeast
		Southwest
		East
		West
		Northeast
		Northwest
		North
Location	Highway access	<1 km
		1–2 km
		2–3 km
		$>$ km
	Distance to substations	<1 km
		1 km–2 km
		2 km–10 km
		>10 km
	Distance to urban areas >5000 inhabitants	<5 km
		5 km–10 km
		>10 km

Table 1 (*continued*)

Criteria	Factors	Indicators
	Distance to urban areas <5000 inhabitants	<1 km
		1 km–5 km
		>5 km
Climate	Global irradiance	4557–4596 Wh/m^2/day
		4596–4636 Wh/m^2/day
		4636–4675 Wh/m^2/day
		4675–4714 Wh/m^2/day
		4714–4754 Wh/m^2/day
		4754–4793 Wh/m^2/day
		4793–4832 Wh/m^2/day
		4832–4872 Wh/m^2/day
		4872–4911 Wh/m^2/day
	Diffuse radiation	0.35%
		0.36%
		0.37%
		0.38%
		0.39%
		0.40%
	Equivalent sun hours (ESH)	1,436–1,452 Kwh/Kwp
		1,452–1,468 Kwh/Kwp
		1,468–1,485 Kwh/Kwp
		1,485–1,501 Kwh/Kwp
		1,501–1,517 Kwh/Kwp
		1,517–1,533 Kwh/Kwp
		1,533–1,550 Kwh/Kwp
		1,550–1,566 Kwh/Kwp
		1,566–1,582 Kwh/Kwp
	Average temperature	15.2–15.8 °C
		15.8–16.4 °C
		16.4–17.0 °C
		17.0–17.6 °C
		17.6–18.3 °C
		18.3–18.9 °C
		18.9–19.5 °C
		19.5–20.1 °C
		20.1–20.7 °C

coastal zone access, or the existence of protected areas, namely, national parks and nature reserves (see Table 2 for a list of the factors defined for each criterion).

Environment, orography, and location criteria indicators and restrictions are predetermined in the model, whereas climate criteria indicators are determined by the interval between the maximum and minimum values given for each factor and zone, and are distributed in homogenous intervals. In this way it was possible to establish sites for grid-connected photovoltaic power plants with maximum energy performance.

Table 2
Negative indicators or restrictions

Criteria	Factors	Indicators
Restrictions	Protected nature reserves	Inside of park Outside of park
	Sites of community interest (SCIs)	Inside SCIs Outside SCIs
	Livestock trails	On the livestock trail Off the livestock trail
	Road networks	Public domain (8 + 25)–(3 + 8) + Affected zone (100 m)–(50 m) Unaffected
	Rivers	Access zone (5 m) + patrolled area (100 m) Unaffected
	Coastal zones	Public domain + Affected zone Unaffected

3.3. Definition of the decision rule

As previously mentioned, the objective in our study is GPPP site selection. To this purpose, a suitable decision rule which integrated the criteria established in accordance with this objective [16], was created. This allowed us to assign a weight to each criterion, factor, and indicator, depending on the influence of each on the performance of the future solar energy installation.

Climate criteria are the most important for the decision rule since they define the electricity production capacity of the photovoltaic power plant. Next come orography criteria, whose importance mainly depends on the steepness or mildness of the slopes in the area. The milder the slopes are, the greater the importance of this type of area since the most suitable sites are those where the ground is flat and oriented towards the south. This research evaluates GGGP site suitability, but not the impacts that such installations might have on the environment. For this reason, environment criteria are third in the order of priorities established in the decision rule.

Finally, location criteria are least in order of importance though they have an important relative weight. In all likelihood, as the sector develops and the prices go down, climate criteria will become less important, and location and environment criteria will become more so.

Saaty's AHP [35] was used to assign weights to each criterion, factor, and indicator, and thus determine their relative importance in the final decision adopted within the model. This method is based on pair-wise comparison within a reciprocal matrix, in which the number of rows and columns is defined by the number of criteria. Accordingly, it was necessary to establish a comparison matrix between pairs of criteria, contrasting the importance of each pair with all the others. Subsequently, a priority vector was computed to establish weights (wj). These weights are a quantitative measure of the consistency of the value judgments between pairs of factors [36].

Before obtaining the comparison matrix, the scale of measurement was determined. Estimated coefficient a_{ij}, which arose from 28 alternative scales, is [26]:

$$S = \left\{\tfrac{1}{9}, \tfrac{1}{8}, \tfrac{1}{7}, \tfrac{1}{6}, \tfrac{1}{5}, \tfrac{1}{4}, \tfrac{1}{3}, \tfrac{1}{2}, 1, 2, 3, 4, 5, 6, 7, 8, 9\right\}.$$

If we call that weight a_{ij}, and use that scale of comparison (see Table 3), and if the relative weighting is $a_{23} = 3/1$, then the relative importance of attribute 3 with regard to 2 is its reciprocal $a_{32} = 1/3$.

Once the values of all the pair-wise comparisons were obtained, it was necessary to design a comparative matrix called **A**. This matrix is square, and has n dimensions (equal to the number of criteria used). Table 4 shows the comparison matrix obtained after applying the decision rule described in the preceding section.

The groups of criteria in the matrix were compared and value judgments assigned to factor pairs. It was then necessary to calculate each factor's weight (*wj*), which is a precise description of the aspects of the value judgments under consideration. Subsequently, a priority vector was computed [36] with a view of establishing a consistency measure for the value judgment assignment (a_{ij}). This assignment can thus be reconsidered in the event that it is found to be inconsistent. The priority vector was calculated after filling out the comparison matrix with the values for the judgments. Normalized values were then obtained for each column, which is the sum of all the values in each column within the

Table 3
AHP weighting scale

Intensity	Definition (i in regards to a j)	Values	Numbers
Relative importance		a_{ij}	a_{ji}
1	Equal importance	1	1
2	Intermediate	2	1/2
3	Moderate importance	3	1/3
4	Intermediate	4	1/4
5	Strong importance	5	1/5
6	Intermediate	6	1/6
7	Very strong importance	7	1/7
8	Intermediate	8	1/8
9	Extreme importance	9	1/9

Table 4
Comparison matrix of the criteria

Critera_1	Environment	Orography	Location	Climate
Environment	1.00	0.33	3.00	0.20
Orography	3.00	1.00	5.00	0.33
Location	0.33	0.20	1.00	0.11
Climate	5.00	3.00	9.00	1.00
Total	9.33	4.53	18.00	1.64

matrix [37]. This process generated an auxiliary matrix in which the value in each cell is the result of the division of each value judgment (a_{ij}) by the sum of the corresponding column (Eq. (1)). Finally, the average of the normalized values of rows was obtained, which corresponds to the priority vector (*wj*). This was normalized by dividing each vector value by n (the number of vectors), thus obtaining the normalized overall priority vector, representing all factor weights (*wj*) (Eq. (2)). These factor weights were then normalized to a certain percentage. Table 5 shows that climate criteria have a weight of 58% in comparison with orography, environment, and location criteria, which have weights of 26%, 12%, and 5%, respectively.

$$A_{ij} = \sum \mathbf{a}_{\text{cb}} / \sum \mathbf{B}, \tag{1}$$

$$(w_j) = \sum \mathbf{A}_i \mathbf{j}/n. \tag{2}$$

3.4. Consistency calculation

This procedure gives the consistency calculation value, which is known as the consistency ratio (CR). In our study, this ratio was determined by Eq. (3), and is based on the quotient of the value of the consistency index (CI), determined by Eq. (4), and the random consistency index (RCI), computed from the average RCI of 500 randomly generated positive reciprocal matrixes. Table 6 gives the *RCI* for various numbers of attributes, represented by n, which, shows the size of the pairwise comparison matrix:

$$\text{CR} = \frac{\text{IC}}{\text{IA}}, \tag{3}$$

Table 5
Matrix for obtaining criteria weights (normalized priority vectors)

Criteria_2	Environment (a)	Orography (b)	Location (c)	Climate (d)	Normalized priority vector W_j	Final weights (%)
Environment (a)	0.11	0.07	0.17	0.12	$\sum A_{ij}/n = 0.1172$	12
Orography (b)	0.32	0.22	0.28	0.20	$\sum B_{ij}/n = 0.2556$	26
Location (c)	0.04	$\mathbf{a}_{bc} = 0.04$	0.06	0.07	$\sum C_{ij}/n = 0.0507$	5
Climate (d)	0.54	0.66	0.50	0.61	$\sum D_{ij}/n = 0.5764$	58
						100

Table 6
Random consistency indexes

No.	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$\mathrm{CI} = \frac{\lambda_{\mathrm{MAX}} - n}{n - 1}. \tag{4}$$

In this expression, n stands for the number of factors in the comparison matrix. λ_{MAX} is the maximum eigenvalue of the comparison matrix A, obtained from its components, which had been previously divided by the number of factors in the matrix. This vector is used to compute consistency as a reflection of the proportionality of the implicit preferences in the value judgments assigned.

For CR values, greater than or equal to 0.10, value judgments should be revised since they are not sufficiently consistent to establish weights (W_j). In contrast, if the CR is less than 0.10, the value judgments are considered to be satisfactory [36].

As an example, we tested the consistency of the values obtained in Table 7. In this case the maximum eigenvalue $\lambda_{\mathrm{MAX}} = 4.07704018$. The values of the CI and CR and of the criteria are 0.02568006 and 0.0285334, respectively. Since CR is less than 0.10, the values in Table 7, assigned to the criteria, are consistent.

Once the criteria were hierarchically organized, and the values found to be consistent, the same process was carried out with the factors and indicators. Table 8 shows the factor values. As can be observed, equivalent sun hours (ESH) is the factor with the most weight (25% out of 100%), followed by global irradiance on horizontal surface (19%). The factor with the lowest value is distance from urban centers of more/less than 5000 inhabitants (1%).

Table 7
Matrix of criteria weights

Criteria_3	Environment	Orography	Location	Climate	Factor *cj*	Factor *dj*
Environment	0.12	0.09	0.15	0.12	0.47	4.01
Orography	0.35	0.26	0.25	0.19	1.05	4.12
Location	0.04	0.05	0.05	0.06	0.20	4.04
Climate	0.59	0.77	0.46	0.58	2.39	4.14

Table 8
Factor weights

Final weight	Value (%)
Land use	5
Visual impact	4
Slopes	9
Orientation	7
Highway access	2
Distance between substations	2
Distance from urban areas with a population of >5000 inhabitants	1
Distance from urban areas with a population of <5000 inhabitants	1
Global irradiance global	19
Diffuse irradiation	11
ESH	25
Average temperature	14
	100

3.5. Determination of the carrying capacity of a territory for grid-connected photovoltaic power plants

The carrying capacity of a territory is established based on the knowledge of land suitability and the possible impact that the area can receive. In other words, the integration of these two elements allows us to establish different carrying capacity levels for the special units that make up the territory in reference to a specific use or activity [16].

Once the weights were obtained, the criteria, factors, and indicators were ordered according to their degree of importance, and normalized on a scale of 0–10, where 0 is the lowest value and 10 is the highest. The following equation was used for the normalization [38]:

$$N = \frac{I - I_{\min}}{I_{\max} - I_{\min}},$$

where N is the normalized value, I the real value, and $I_{\min}$ and $I_{\max}$ are the minimum and maximum values of the scale of values to be normalized.

The next step was to enter the indicators, factors, and criteria into a GIS. For this purpose, a value was normalized and assigned to each model on a scale from 1 to 10, where 1 is the lowest suitability and 10, the highest. The tools used for this were the mapping software package ArcView 3.2 and the spatial analyst extension, which includes Model Builder. Model Builder can be used to study the relation between different information levels that occupy the same geographic space, and thus obtain a hierarchical organization of the layers.

Finally weighted overlay was applied to all these layers. Burrough and McDonnel [39] define this technique as the superimposition of digital representations of various sets of spatial data in such a way that each position in the area can be analyzed in terms of this data. This process makes it possible to create an output that combines all the characteristics of the input layers within one geographic area. This provides information related to the site suitability of GPPPs, and facilitates the decision-making process for policy makers and stakeholders.

4. Testing the model

4.1. Area of study

Because of the geographical extension of Andalusia it would have been extremely complex to apply our model to its entire surface area. For this reason, the area selected was located on the plateau of Granada, namely the district of Huéscar, located between the provinces of Almería, Albacete, and Jaén.

Huéscar is situated in the far northeast of the province of Granada, approximately, between latitudes 38°05′N and 37°46′N and longitudes 2°44′W and 2°26′W, relative to the Greenwich Meridian (see Fig. 2). With an area of 1782 km^2, Huéscar is the largest district in the province of Granada. The two defining characteristics of its climate are its altitude (between 900 and 2,383 m) and isolation because of the surrounding mountain range.

This area was selected because it is representative of all the uses considered in the model. Furthermore, its principal climate features are ideal for the optimal performance of photovoltaic power plants. The orography of this region is made up of totally flat areas, as

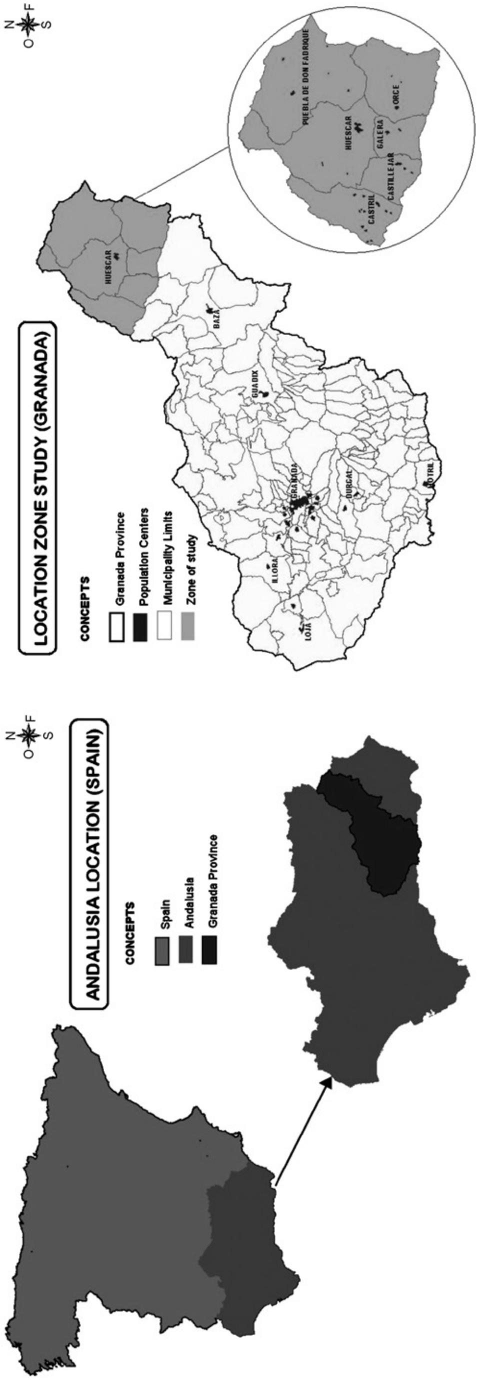

Fig. 2. Geographic location of the area of study.

well as other areas with dramatic irregularities, such as La Sagra, a mountain with an altitude of almost 2500 m. The application of the model to this area allowed us to test the behavior of each variable in the final result.

4.2. Obtaining layers

During this phase we generated layers related to criteria, factors, and both positive and negative indicators. We used the database of land uses and livestock trails in Andalusia (Department of the Environment of the Andalusian Regional Government), the database of Andalusian highway and road networks (Department of Public Works of the Andalusian Regional Government), database of hydrographic systems in Andalusia, database of sites of community interest (SCIs) in Andalusia, and the database of national parks and protected nature reserves in Andalusia.

The area chosen for our study includes the Sierra de Castril, an important landmark, which includes La Peña, where the Castle of Castril is located and the SCIs of the mountain ranges in the northeast. The cattle trails in the area include narrow mountain passes, paths, animal tracks, and livestock trails. The generation of the other layers, all of which are specific to Andalusia, was carried out by the authors of this research study. These include average annual daily temperatures, annual solar irradiation on horizontal surfaces, diffuse solar radiation, annual ESH, location of electricity substations, visual impact, slope, and orientation.

Once the layer of indicators was established and made discrete by means or arithmetic overlay, the layers of factors were also obtained. The result of the factors was reclassified (reclass) and normalized to obtain the layer of criteria to be analyzed by weighted overlay. With this technique each of the input layers was assigned a weight, which is a percentage of its importance in the model. The sum of all of the weights is 100%. Fig. 3 shows an example of the land use indicators. As can be observed, the figure shows that the

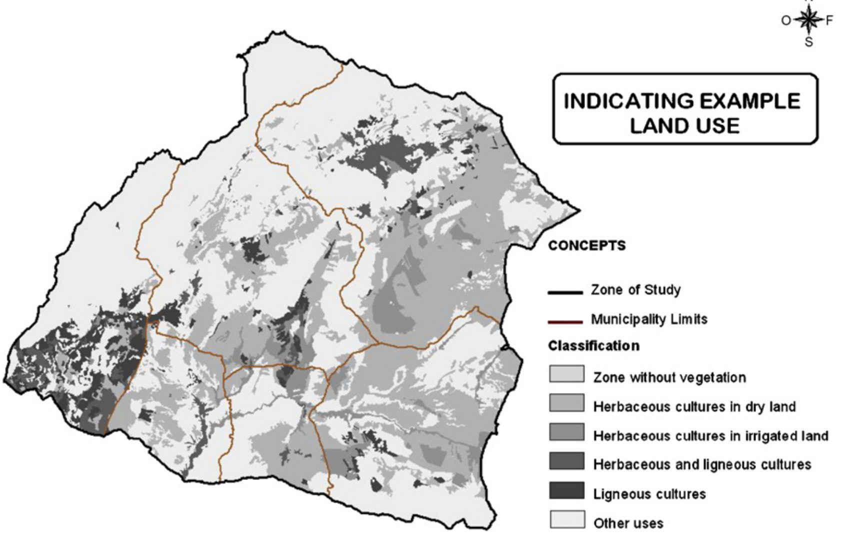

Fig. 3. Map of land use indicators.

predominant land uses are dryland crops and other crops, which is in consonance with the actual land uses in the study area.

Fig. 4 shows an example of the layer for negative indicators or restrictions. It shows a large area to the north, which was excluded from our study, because it is the location of the Sierra de Castril Nature Reserve. Although there is no law expressly prohibiting the installation of photovoltaic power plants in this area, we decided that it was best to focus on land with a lower ecological value before considering land with a great quantity of flora and fauna, or land that could be used for agricultural exploitation. The other areas excluded are those with highway access rights or protected surface waterways.

Fig. 5 shows an example of a map of the slope factor. As can be observed, the study area has sectors that are completely flat, whereas others are very mountainous.

Finally, Fig. 6 is an example of the hierarchical representation of climate criteria. The figure shows that the north sector has values between 7 and 10, and thus from a climate perspective, offers the best conditions for GPPP sites, whereas the south and southwest sectors have lower values (between 1 and 2).

4.3. Site suitability for GPPPs in the study area

The analysis of the carrying capacity in the study area was carried out by adding the layers specified in the previous phase by means of arithmetic overlay. This result was also normalized and reclassified (reclass), Fig. 7 shows the final layer thus obtained.

As can be observed, the study area does not show the presence of the lower levels of the final layer (i.e. values 1–3). Since there is not any land with the maximum value for each factor, layer 10 is uncompleted. This is because a large sector of the study area is not suitable for GPPP sites. Most of its surface is located in protected areas, highway access zones, rivers, etc. in the north as shown in Fig. 7.

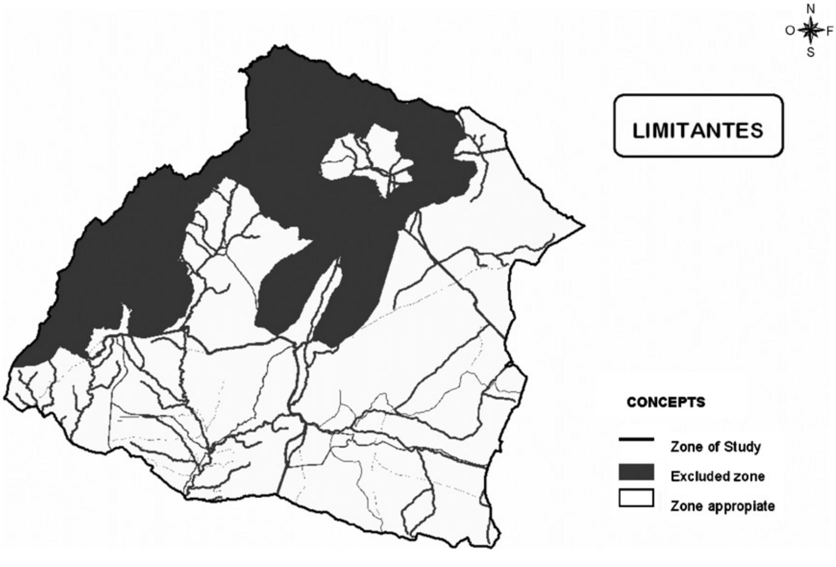

Fig. 4. Map of restrictions.

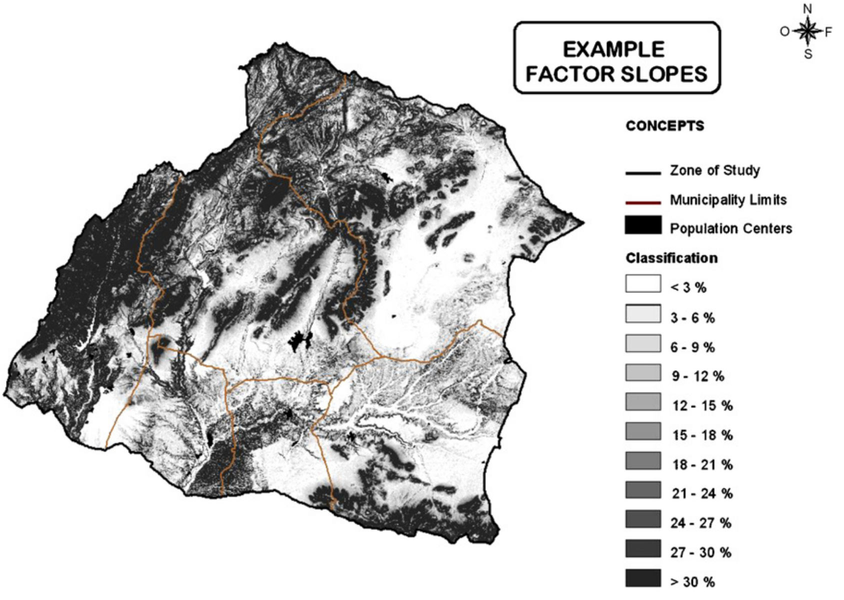

Fig. 5. Slope map.

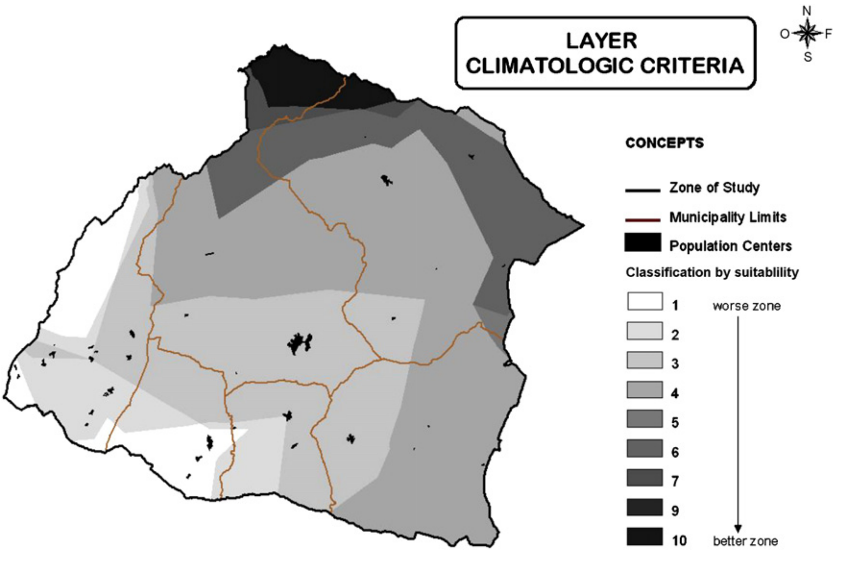

Fig. 6. Climate map.

Fig. 8 shows the surface distribution obtained in the final result of the model. The highest number indicates the number of hectares of land obtained for the value, specified in abscissas. The second value is the percent corresponding to the percentage of plots over the total, which correspond to the value of the abscissas.

There is a large surface area with values of 7–9. This signifies that in this area there are many suitable sites for the location of GPPPs because of their favorable climate (high

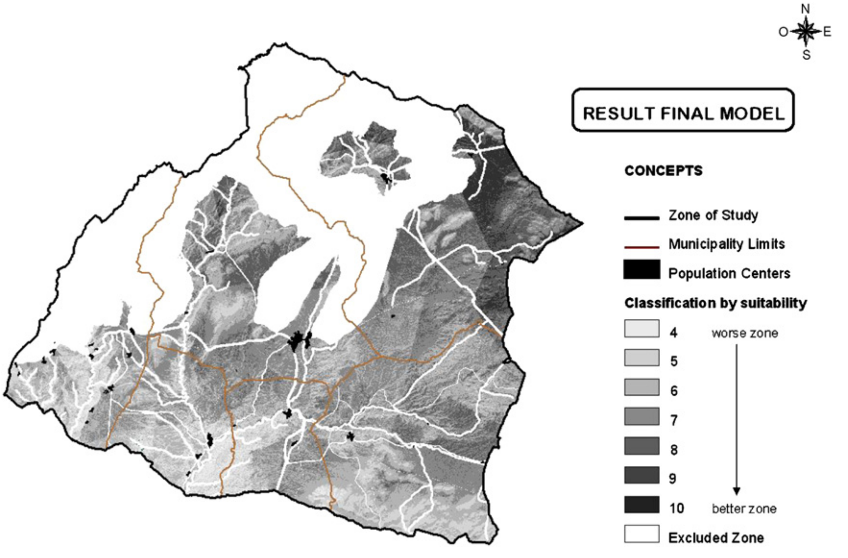

Fig. 7. Final result layer.

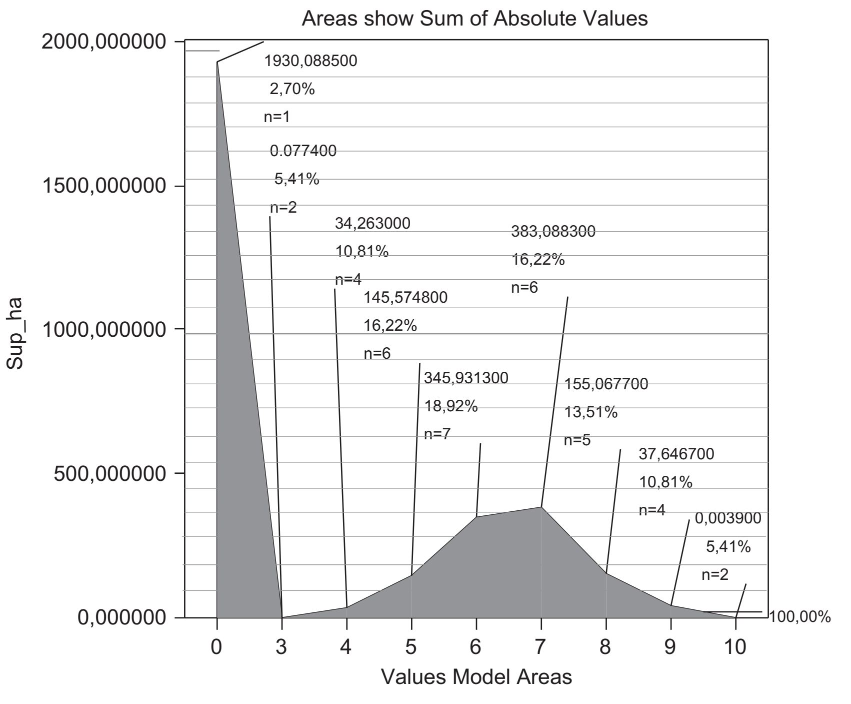

Fig. 8. Surface distribution obtained in the final result.

number of sun hours per year), moderate annual average temperatures, and high level of global irradiation on a horizontal surface.

Except for the exclusion zones defined by the boundary layers, the land has a very low agricultural or environmental value. There are ample surfaces with dryland that is uncultivated or with herbaceous vegetation, which are very suitable for our objectives. However, even though this is not the purpose of our study, the area was found to have deficient power transmission networks, which should be improved with a view to making the area more valuable, and using it specifically for the production of electricity with renewable energies.

4.4. Validation of the model

The final phase in the construction of a model should be its validation in order to guarantee that it offers a reliable representation of the systems represented. This validation process consists of three components [40]:

1. Verification
2. Validation
3. Sensitivity analysis.

The verification of a model means checking to see if the results fulfill the entry requirements; in other words, if the model has been correctly designed by making sure that the criteria followed in the decision rule are correct. As previously mentioned, this validation determines if the model is suitable for the purpose it was designed for. For example, it checks if the pixels, showing the existence of a river at a certain set of coordinates, correspond to the existence of the river in the real world.

In our study, as in Pozzobon [37], the following validation techniques were applied to the representative zones in the study area:

- *Validation pixel by pixel*: Pixels were selected in each of the categories of the resulting areas to subsequently confirm their conditions in the map of each factor. In this way, we verified that the information contained in the pixels in the map of results coincided with the information contained in the factor maps.
- Visual analysis and comparison of the layers with the highest values in the model with the optimal site locations for GPPPs in the study area.
- *On-site validation*: For this purpose we carried out field studies to confirm in situ that the characteristics of the study area such as highway accesses, rivers, distance to substations, etc. actually exist in real life as they appear described in the map.

The first zone, as shown in Fig. 9, is located in the northeast. This is where the most suitable sites are located, and which have the most optimal conditions: flat land with herbaceous crops, a high level of solar radiation, moderate temperatures, and a favorable location. This area has a series of distinctive features. For example, in the strip of land situated to the north there is a straight line going from east to west as can be observed in detail (1). This strip is the result of the difference between two sectors with different climate values. It is also a transition zone in which the land goes from being flat to mountainous with steep slopes and natural vegetation. This makes it the least suitable surface for our

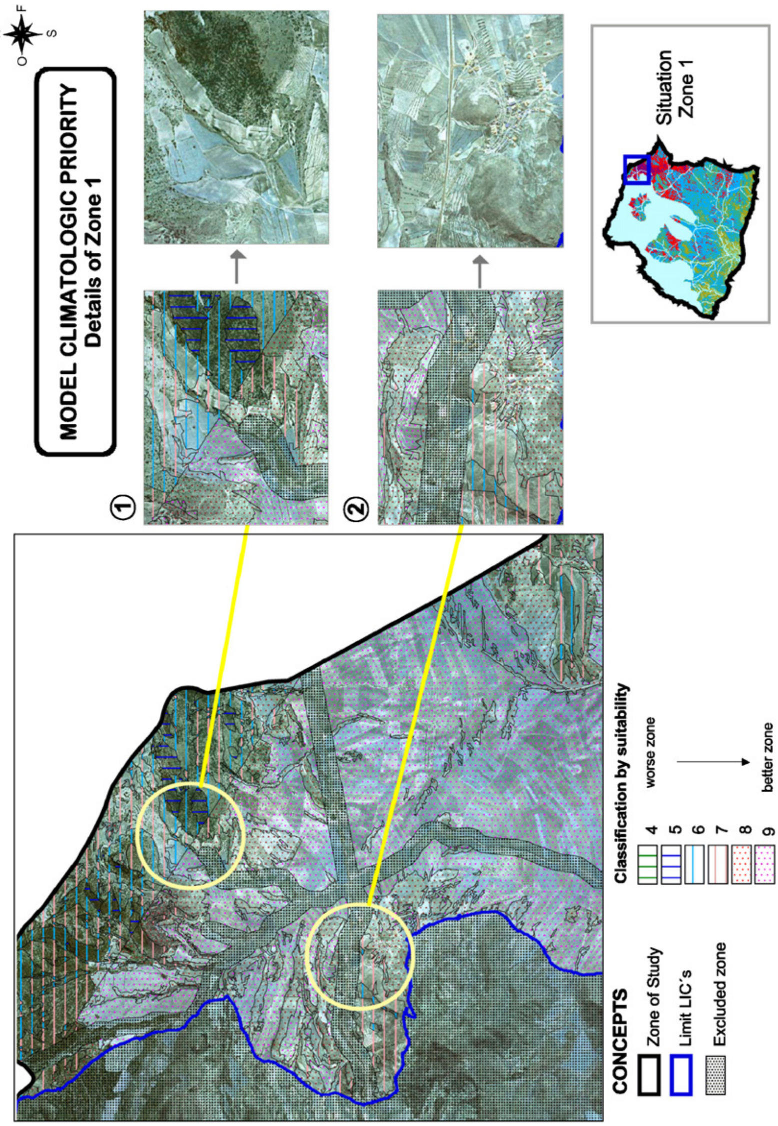

Fig. 9. Results from Zone 1 for the validation of the model.

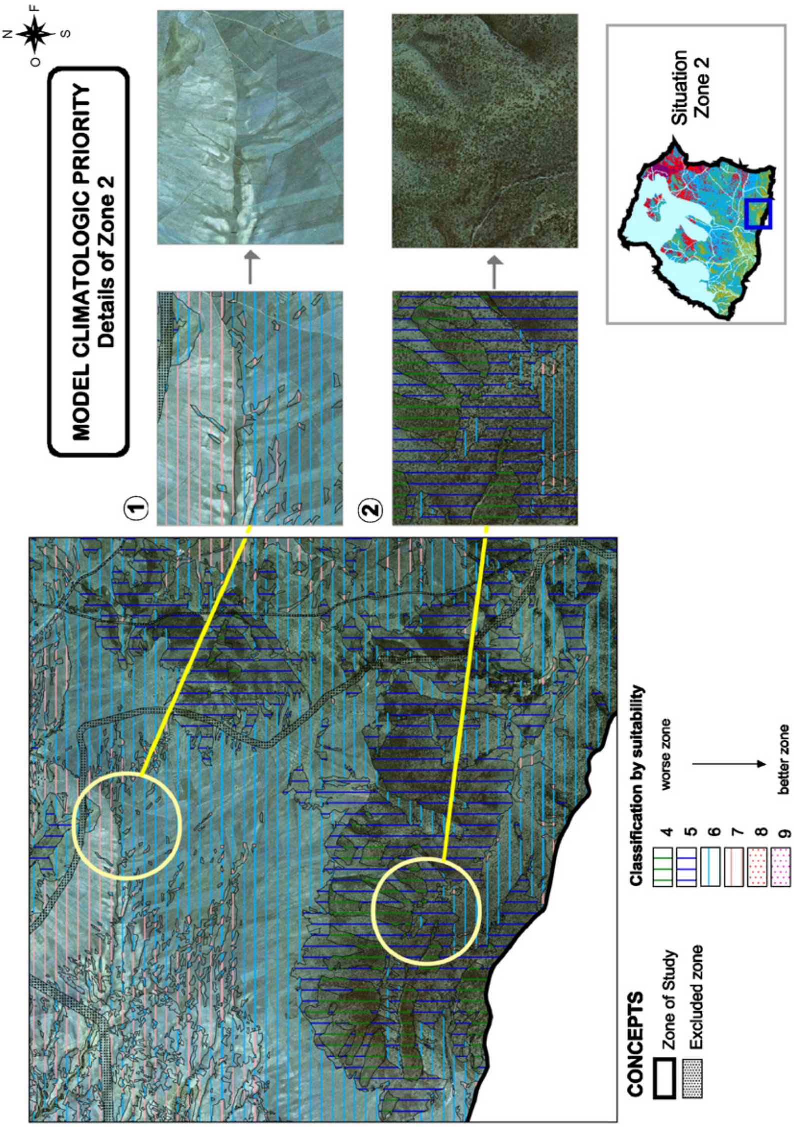

Fig. 10. Results from Zone 2 for the validation of the model.

purposes. Detail (2) in Fig. 14 shows the exclusion of the area of access to highway A-33 as well as the proximities to Almaciles, an urban population center. The red line in the figure separates a zone declared as a site of community interest, which includes the northeast mountain ranges.

The second zone, located to the south, is shown in Fig. 10. It includes the land with intermediate and low suitability due to the fact that its climate conditions and other factors are not favorable for the purposes of our study. The first detail of this figure shows a zone of only intermediate suitability, despite the fact that it is a flat area with dryland herbaceous crops. Its low rating is the result of its climate conditions. The second detail shows a mountainous area with thickets and scrubland, steep slopes, and a poor location because of its distance from urban centers and highways. All these circumstances make it one of the least suitable sites within our study area.

5. Conclusions

The model developed as part of our research study helps technicians to determine the optimal sites for GPPP installations. As explained in the previous sections, this model takes into account: (i) climate features that directly influence the performance of solar energy installations, (ii) environmental aspects such as land use, (iii) legal aspects regarding the protected areas of this land, (iv) orography and (v) location.

The MCE and the AHP for priority assignment, combined with GIS allowed us to verify the values assigned to each criterion and factor, based on the CIs obtained. GISArcView 3.2 and its extensions showed themselves to be extremely useful tools to systematically process the great quantity of information obtained for a very important geographic location.

In the example given, the resulting layers were found to have a very high rating on the scale of values. Accordingly, the area of study, with the exception of the excluded zones, was considered to be suitable for high-performance GGGP sites, which would have little or no negative impact on the environment.

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